RESEARCH HIGHLIGHT

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Effect of Mesh and Bale Orientation on the Strength of Straw Bale Walls

INTRODUCTION

Straw bale construction has experienced an increase in popularity since the mid-1990s. While actual examples of straw bale homes have shown that the wall system performs in accordance with the intent of Canadian building codes, there is currently a lack of codes and accepted standards for straw bale construction. Prospective straw bale homeowners, designers and builders have had to rely on a range of small-scale testing performed around the world to varying standards in order to make design and engineering decisions on the construction methods for their walls.

There are many approaches that can be taken to building a straw bale wall system. The bales can be aligned in two different ways within the wall (flat or on edge); different plasters can be used on the straw (cementitious or clay-based); different methods can be used to help the plaster adhere to the straw walls (bare straw, mesh or slip coats); and different beam structures can be used at the top of a wall to affix roof structures and transmit loads to the bale walls.

Funded under CMHC's External Research Program, this research study compared single, full-scale wall examples of many of these variables in an attempt to quantify the performance of the different combinations.

This study took a minimalist approach in order to establish a low-end performance baseline rather than over-build the samples to get the best possible results. Straw bale walls are often chosen by owners and builders seeking to lower material use and environmental impacts of construction, and the test samples minimize the use of lumber and plaster.

RESEARCH PROGRAM

The objectives of this study were:

- to use a lightweight beam structure on each of the wall samples to limit the effect of the beam's strength on the overall strength of the bale wall;
- to load the beam structure so that it accurately reflects the way roof framing imposes loads on a wall;
- to compare walls with bales oriented flat and on edge;
- to compare walls with bales plastered with cement–lime plasters and clay plasters;
- to compare walls with plasters applied directly to the straw and applied over mesh and slip coats.

The construction method was the same for every wall sample, and the researchers tested only one of each type of wall configuration.

Typical, two-string bales of wheat straw were used for all the walls. The bales were of a size and density that would be considered average to lower-than-average for the construction of typical walls.

Each wall was built to allow the imposed compressive loads to be transmitted directly into the plaster skins on the bales and to ensure that the plaster skins were supported as though they were bearing directly on the foundation of a building.

A ladder-style box beam was used on top of the wall. This box beam used two parallel 2x4 (38x89 mm) sides spaced apart with 2x4 blocking at 600 mm (24 in.) centres and 12 mm (1/2 in.) plywood on the bottom. This box beam was smaller and lighter than a box beam typically used in construction, which normally uses 2x6 or 2x8 box beams.

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The box beams were 2 in. (50 mm) wider than the bales. With the bales centred under this beam, the additional inch (25 mm) on either side acted as a plaster stop and allowed the beam to transfer loads directly into the plaster skins.

All the walls were 2.4 m (8 ft.) high, typical for home construction. For bales laid flat, six courses reached 2.4 m; for bales laid on edge, five courses reached 2.3 m. Each wall was 2.4 m long, with two and one-half bales per course laid in typical running bond.

Two nylon bands on each wall provided some pre-tensioning of the wall system before plastering. The amount of tension placed on the straps was not measured and would be considered very minimal compared to typical practice. Tensioning was applied once per strap and there was no further tightening.

The bales were not trimmed before plastering and gaps between bales were not methodically stuffed, because of time and space limits, which is common in typical construction.

The cement–lime plaster was one part St. Lawrence Mason's Choice Type N masonry cement to three parts fine-screened masonry sand and clean water to provide a workable consistency. This plaster was applied in two coats by steel trowel, with some mechanical scoring of the first coat before application of the second coat.

The clay plaster was one part Mar-Co Turface Mound Clay to three parts fine-screened masonry sand and a quantity of unchopped wheat straw collected from the floor after the cutting and retying of the bales. Clean water was added to provide a workable consistency. This plaster was applied by hand in two coats.

A set of three 50 mm (2 in.) cubes of each plaster mix were tested in compression following ASTM C109 (1998) to measure the compressive strength of the plaster.

The meshed walls were Tenax Cintoflex D, a polypropylene mesh commonly used by bale builders. This mesh has rectangular openings 25 mm (1 in.) by 40 mm (1.5 in.). The mesh is cut to the size of the wall and stapled to the box beam and the sill plates before being sewn to the wall using baling twine passed from one side of the wall to the other.

The slip-coated walls had a runny mixture of clay and water applied to the straw by hand before stacking. Typical practice would be to dip the bales into a pool of clay slip or to spray the slip onto the bales with a pump.

The prepared walls were given approximately 30 days to cure inside the lab at a constant temperature of 20°C (68°F). They were then subjected to a compressive load under a steel loading frame. A movable hydraulic ram was mounted on the frame and used to apply the compressive loads to the walls through a specially designed steel loading plate. Small, steel-box sections were welded to the bottom of the loading plate every 600 mm (2 ft.) to simulate the load transfer through the roof framing to the box beam.

Each test was monitored using a load cell and linear voltage displacement transducers (LVDTs) to measure both vertical and lateral deflections.

RESULTS

Each of the 10 walls was tested to failure, with the exception of one sample that reached the maximum capacity of the load cell without failure. Each of the walls responded to the compressive loading in a similar manner. A small amount of deflection was recorded immediately as the top plate was pushed into contact with the plaster skins, which shrank away from the beam during curing. The wall would then accept loading with linear behaviour up to the ultimate load. After reaching the ultimate load, each wall exhibited a rapid increase in deflection and a loss of load as the plaster cracked.

Walls with bales laid flat tended to deform uniformly and generally failed by vertical crushing with little lateral bending. Walls with bales on edge generally failed by bending laterally and buckling. Failure was typically preceded by widespread cracking of the plaster and accompanied by delaminating of the plaster from the straw surface.

There were two types of post-failure behaviour, depending on whether cement–lime or clay plaster was used. For walls with cement–lime plaster, the peak load was followed by a steep reduction in load. For walls with clay plasters, the drop in load after failure was not nearly as dramatic.

Following the failure of the plaster, most of the strength of the wall was provided by the straw bales, which carry approximately 40 kilonewtons—kN—about 9,000 lb.—when the bales are flat and 20 kN (about 4,500 lb.) when the bales are on edge. No wall failed catastrophically and following failure each wall remained standing and had significant post-failure capacity.

CONCLUSIONS

The following are the conclusions that follow from this research:

- Straw bale walls with cement/lime plasters have ultimate average strengths of 3.3 MPa (480 psi) and range between 1.9 MPa (280 psi) and 5.6 MPa (810 psi).
- Straw bale walls with clay plasters have ultimate average strengths of 0.5 MPa (73 psi) and range between 0.3 MPa (44 psi) and 1.0 MPa (150 psi).
- The measured strength of the cement–lime walls ranges between 8 per cent and 18 per cent of the theoretical strength based on the cube strength of the plasters and the nominal plaster thickness on the walls. The low strength of these walls compared to the theoretical value appears to be related to local buckling of the very stiff plaster.
- The measured strength of the clay plaster walls ranges between 50 per cent and 102 per cent of the theoretical strength.
- Bale orientation has little effect on the compressive strength of a wall if cement–lime plaster is used.
- Walls with bales oriented flat are about 56 per cent stronger than walls with bales oriented on edge when clay plasters are used.
- Mesh does not improve the compressive strength of straw bale walls with cement–lime plaster, and in fact may decrease the strength by affecting the plaster-straw bond, leading to premature local buckling of the plaster. The mesh does, however, bridge cracks that develop after failure of a wall in compression, allowing the wall to undergo large lateral deflections without collapse.
- Clay slip does not improve the compressive strength of straw bale walls with clay plasters.
- Because of the wide variation of plaster thickness when hand plastering was used, the plaster was not being used efficiently from a structural point of view.

IMPLICATIONS FOR THE HOUSING INDUSTRY

The single sample of each wall type in this study gives designers and builders some good general guidelines for straw bale wall assemblies. It also points to some important conclusions; to the need for more research in some areas; and to tests with a larger number of samples.

The wall strengths with cement–lime plasters with the bales in either orientation supports existing research showing that these walls are adequate load-bearing structural walls for most residential construction, including two-storey buildings.

The loading capacity and failure modes of the walls indicate that the plaster skins should bear roof loads directly and be supported fully by the foundation.

The wall strengths achieved using a lightweight 2x4 box beam shows that designers need not rely on larger-dimension beams when loads are transferred directly into the plaster skins in wall sections with no openings.

The wall strengths achieved using poor-to-average quality bales show that builders do not need to find bales of exceptional compaction or density to achieve adequate compressive strength.

The addition of mesh to a bale wall does not improve compressive strength. Builders must ensure that, if mesh is being used to make it easier to apply plaster to the wall, the mesh must not prevent the plaster from making full contact with the straw behind the mesh. Wall sections where plaster is stuck only to the mesh will be the first to fail.

The controlled and non-catastrophic failure mode of the walls indicates a positive safety factor in the wall system when imposed loads are much greater than anticipated.

The plaster skins on a bale wall are only as strong as their minimum thickness. Even when the average thickness indicates a certain level of ultimate strength, failure will occur earlier where the plaster is thinnest. Builders should pay close attention to the vertical alignment level of the bales in the wall and ensure that the minimum plaster thickness is achieved over the entire surface of the wall. Points of excess thickness do not increase the strength of the wall.

The low ultimate strength figures for the clay-plastered walls show that more work is required to ensure adequate plaster strength and thickness when using clay plasters. The variable nature of clay plasters indicates that samples of clay plasters should be properly tested before use to ensure adequate strength. Other studies have shown clay plaster strengths many times higher than those achieved in this study.

The wide range of aggregate sizes typically found in site soils as compared to the uniform particle size in the masonry sand used in this study may play an important role in the strength of clay plasters. Finely chopped straw fibre may provide more strength than the long straw used in this study.

The thickness of clay plasters is typically greater than those achieved in this test, tending to be 40–50 mm (1.5–2 in.) The effect of plaster thickness on ultimate wall strength shown in this study indicates that applying a thicker coat of clay plaster will have a large affect on the strength of the wall.

The design and construction of straw bale walls will continue to evolve. The directions indicated by the results of this study should help to inform and improve current practice.

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